

Hint of CPT Violation in Short-Baseline Electron Neutrino Disappearance

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We analyzed the electron neutrino data of the Gallium radioactive source experiments and the electron antineutrino data of the reactor Bugey and Chooz experiments in terms of neutrino oscillations allowing for a CPT-violating difference of the squared-masses and mixings of neutrinos and antineutrinos. We found that the discrepancy between the disappearance of electron neutrinos indicated by the data of the Gallium radioactive source experiments and the limits on the disappearance of electron antineutrinos given by the data of reactor experiments reveal a positive CPT-violating asymmetry of the effective neutrino and antineutrino mixing angles (with a statistical significance of about 3.5σ), whereas the squared-mass asymmetry is practically not bounded.

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The radioactive source experiments performed by the GALLEX [1–3] and SAGE [4–7] collaboration for testing the respective Gallium solar neutrino detectors revealed a disappearance of electron neutrinos with energy E of the order of 1 MeV at a distance L of the order of 1 m. Since the ratio L/E is of the order of 10 eV^{-2} , the disappearance could be due to short-baseline oscillations (see Ref. [8]) generated by a squared-mass difference $\Delta m^2 \gtrsim 0.1\text{ eV}^2$ [9–17] and a large effective mixing angle ϑ , such that $\sin^2 2\vartheta \gtrsim 0.1$ [17]. On the other hand, the measurements of reactor electron antineutrino experiments constrain $\sin^2 2\vartheta$ below about 0.1 [13, 18, 19], assuming that the survival probabilities of neutrinos and antineutrinos are equal, as implied by the CPT symmetry (see Ref. [8]).

We can test the compatibility of electron neutrino disappearance in Gallium radioactive source experiments with the reactor constraints through a calculation of the corresponding parameter goodness-of-fit [20]. We use the fit of Gallium data presented in Ref. [17] and the fit of the Bugey [18] and Chooz [19] reactor data presented in Ref. [13], taking into account also the constraints given by the results of the Mainz [21] and Troitsk [22] Tritium β -decay experiments as described in Ref. [15]. For the parameter goodness-of-fit (GoF) we obtain

$$\Delta\chi_{\min}^2 = 12.1, \quad \text{NDF} = 2, \quad \text{GoF} = 0.2\%, \quad (1)$$

where NDF is the number of degrees of freedom and $\Delta\chi_{\min}^2$ is the difference between the χ_{\min}^2 obtained in the combined analysis and the sum of the χ_{\min}^2 's obtained in the separate analyses of Gallium data and reactor plus Tritium data.

Therefore, electron neutrino disappearance in Gallium radioactive source experiments is rather incompatible with the reactor constraints on the disappearance of electron antineutrinos and we are lead to study the possibility of CPT violation which can generate a difference of the survival probabilities of neutrinos and antineutrinos.

CPT symmetry is widely believed to be exact, because it is a fundamental symmetry of local relativistic Quantum Field Theory (see Ref. [23]). However, it is possible to extend the Standard Model Lagrangian by including CPT and Lorentz violating terms [24–26].

We are stimulated in considering CPT violation by the recent indication in favor of CPT violation found in the MINOS long-baseline ν_μ and $\bar{\nu}_\mu$ disappearance experiment [27, 28]. The MINOS data indicate for ν_μ and $\bar{\nu}_\mu$ different values of the effective squared-mass differences and mixings. Also the difference between the absence of $\nu_\mu \rightarrow \nu_e$ oscillations in the data of the short-baseline MiniBooNE experiment [29] and the indication in favor short-baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations which are compatible with the LSND signal [30] found recently in the MiniBooNE experiment [31, 32] may be due to different values of the effective squared-mass differences and mixings of neutrinos and antineutrinos [33]. Such difference in the fundamental properties of neutrinos and antineutrinos are possible if the theory is nonlocal [34].

Hence, we consider the simplest case in which short-baseline disappearance of electron neutrinos and antineutrinos are given by effective two-neutrino like oscillation probabilities governed by different effective squared-mass differences and mixings [15, 33, 35–47], Δm_ν^2 and $\sin^2 2\vartheta_\nu$ for neutrinos and $\Delta m_{\bar{\nu}}^2$ and $\sin^2 2\vartheta_{\bar{\nu}}$ for antineutrinos:

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\vartheta_\nu \sin^2 \left(\frac{\Delta m_\nu^2 L}{4E} \right), \quad (2)$$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{\bar{\nu}} \sin^2 \left(\frac{\Delta m_{\bar{\nu}}^2 L}{4E} \right). \quad (3)$$

These survival probabilities can be obtained in a CPT-

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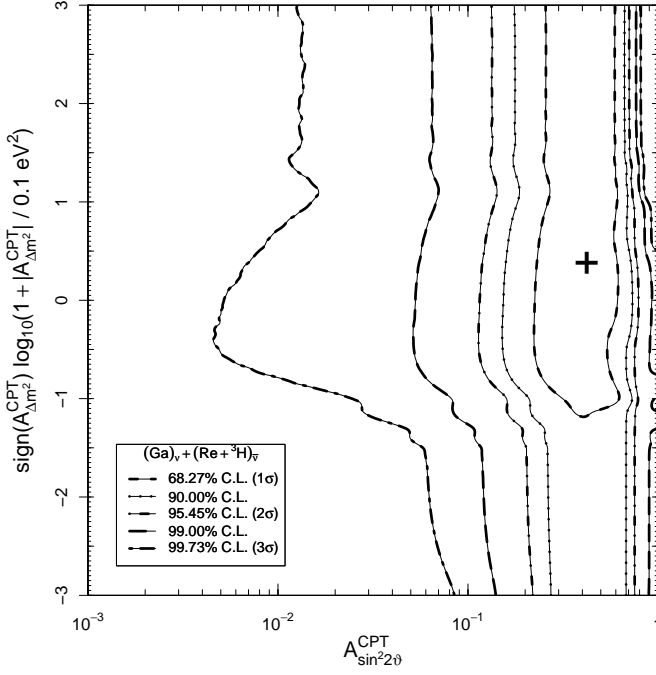


FIG. 1. Allowed regions in the $A_{\sin^2 2\vartheta}^{\text{CPT}} - A_{\Delta m^2}^{\text{CPT}}$ plane. The best-fit point corresponding to χ_{\min}^2 is indicated by a cross.

violating version of four-neutrino mixing schemes (see Refs. [48, 49]) as hypothesized in Ref. [33]. Four-neutrino mixing schemes are the simplest extensions of the standard three-neutrino mixing schemes which can accommodate the two measured small solar and atmospheric squared-mass differences $\Delta m_{\text{SOL}}^2 \simeq 8 \times 10^{-5} \text{ eV}^2$ and $\Delta m_{\text{ATM}}^2 \simeq 2 \times 10^{-3} \text{ eV}^2$ and one larger squared-mass difference for short-baseline neutrino oscillations, $\Delta m^2 \gtrsim 0.1 \text{ eV}^2$. The existence of a fourth massive neutrino corresponds, in the flavor basis, to the existence of a sterile neutrino ν_s .

We analyze Gallium data and reactor plus Tritium data in terms of the mass and mixing asymmetries

$$A_{\Delta m^2}^{\text{CPT}} = \Delta m_\nu^2 - \Delta m_{\bar{\nu}}^2, \quad (4)$$

$$A_{\sin^2 2\vartheta}^{\text{CPT}} = \sin^2 2\vartheta_\nu - \sin^2 2\vartheta_{\bar{\nu}}. \quad (5)$$

The best-fit values of the asymmetries are

$$(A_{\sin^2 2\vartheta}^{\text{CPT}})_{\text{bf}} = 0.42, \quad (A_{\Delta m^2}^{\text{CPT}})_{\text{bf}} = 0.37 \text{ eV}^2. \quad (6)$$

The allowed regions at 68.27%, 90%, 95.45%, 99% and 99.73% C.L. for $A_{\sin^2 2\vartheta}^{\text{CPT}}$ and $A_{\Delta m^2}^{\text{CPT}}$ are shown in Fig. 1. We used a logarithmic scale for $A_{\sin^2 2\vartheta}^{\text{CPT}}$, considering only the interval $10^{-3} \leq A_{\sin^2 2\vartheta}^{\text{CPT}} \leq 1$ which contains all the allowed regions. For $A_{\Delta m^2}^{\text{CPT}}$ we used an antisymmetric logarithmic scale, which allows us to show both positive and negative values of $A_{\Delta m^2}^{\text{CPT}}$, enlarging the region of small values of $A_{\Delta m^2}^{\text{CPT}}$ between 0.1 and 1 eV^2 .

The best-fit value $(A_{\Delta m^2}^{\text{CPT}})_{\text{bf}}$ of the mass asymmetry is small, but Fig. 1 shows that in practice any value of the

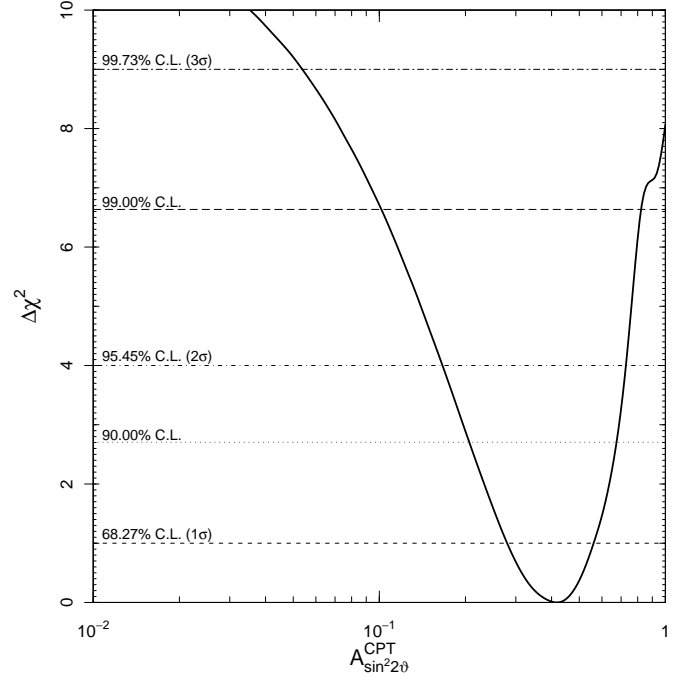


FIG. 2. Marginal $\Delta\chi^2 = \chi^2 - \chi_{\min}^2$ for $A_{\sin^2 2\vartheta}^{\text{CPT}}$. The $\Delta\chi^2$ of the horizontal lines correspond to the indicated value of confidence level.

mass asymmetry is allowed, with a slight preference for positive values. On the other hand, we obtain a very interesting result for the mixing asymmetry: the best-fit value $(A_{\sin^2 2\vartheta}^{\text{CPT}})_{\text{bf}}$ is large and positive and Fig. 1 shows that zero or negative values are disfavored.

From Fig. 1 one can see that the smallest value of $A_{\sin^2 2\vartheta}^{\text{CPT}}$ included in the 3σ allowed region is about 0.005 at $A_{\Delta m^2}^{\text{CPT}} \simeq -0.15 \text{ eV}^2$. However, since in practice $A_{\Delta m^2}^{\text{CPT}}$ is not bounded, the statistically reliable limits on $A_{\sin^2 2\vartheta}^{\text{CPT}}$ are given by the marginal $\Delta\chi^2 = \chi^2 - \chi_{\min}^2$ function for $A_{\sin^2 2\vartheta}^{\text{CPT}}$ depicted in Fig. 2. One can see that $A_{\sin^2 2\vartheta}^{\text{CPT}} > 0.055$ at 3σ .

The marginal $\Delta\chi^2$ of a null asymmetry ($A_{\sin^2 2\vartheta}^{\text{CPT}} = 0$) is 12.0, with an associated p-value of 0.05%. Hence, there is an indication of a positive asymmetry $A_{\sin^2 2\vartheta}^{\text{CPT}}$ at a level of about 3.5σ .

The indication in favor of a CPT asymmetry that we have found is robust, because it is obtained by confronting the observations on the disappearance of electron neutrino and antineutrino, which should be equal if the CPT symmetry is not violated. We considered the simplest case of a difference of the effective squared-masses and mixings of neutrinos and antineutrinos. The analysis of the data in the framework of other, more complicated, models would lead to a similar indication of a CPT asymmetry in the space of the parameters of the specific model under consideration.

Our results depend on the hypothesis that the anomalous deficit of electron neutrinos measured in the radioac-

tive source experiments is due to neutrino oscillations [10–17], taking into account the uncertainty of the detection cross section [50–52] as discussed in Ref. [17]. The experimental significance of the anomaly can be tested by the new Gallium radioactive source experiment proposed in Ref. [16]. However, a crucial improvement needed for understanding the validity of the neutrino oscillation hypothesis is an accurate calculation of the ν_e - ^{71}Ga detection cross section and its uncertainty, improved with respect to the existing ones [51, 52].

The short-baseline disappearance of electron neutrinos can be tested in the future not only with new Gallium radioactive source experiments, but also with accelerator experiments with a well-known flux of electron neutrinos, as discussed in Ref. [15].

For the investigation of the CPT asymmetry, the ideal experiments are those which can measure the disappearance of both electron neutrinos and antineutrinos, with sources which emit well-known neutrino and antineutrino fluxes and detection processes with well-known cross sec-

tions. Experiments of this type are near-detector beta-beam [53] and neutrino factory [46, 54] experiments, which are under study but may require a long time to be realized. In a shorter time it may be possible to perform dedicated experiments with intense artificial radioactive sources of electron neutrinos and antineutrinos placed inside or close to neutrino elastic scattering detectors with a low energy threshold, as Borexino [55] or a low-threshold liquid Argon TPC [56].

In conclusion, we have found an indication of a CPT-violating asymmetry in the short-baseline disappearance of electron neutrinos and antineutrinos by confronting the neutrino data of the Gallium radioactive source experiments and the antineutrino data of the reactor Bugey and Chooz experiments. Considering the simplest case of a difference of squared-masses and mixings of neutrinos and antineutrinos, we found that the squared-mass asymmetry is practically not bounded, whereas the mixing asymmetry is positive with a statistical significance of about 3.5σ .

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